



Munoz, E., Arumí, J. L., Wagener, T., Oyarzun, R., & Parra, V. (2016). Unraveling complex hydrogeological processes in Andean basins in south-central Chile: an integrated assessment to understand hydrological dissimilarity. *Hydrological Processes*, 30(26), 4934–4943. <https://doi.org/10.1002/hyp.11032>

Peer reviewed version

Link to published version (if available):
[10.1002/hyp.11032](https://doi.org/10.1002/hyp.11032)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the accepted author manuscript (AAM). The final published version (version of record) is available online via Wiley at <https://doi.org/10.1002/hyp.11032>. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Unraveling complex hydrogeological processes in Andean basins in south-central Chile: An integrated assessment to understand hydrological dissimilarity

Journal:	<i>Hydrological Processes</i>
Manuscript ID	HYP-15-0875.R2
Wiley - Manuscript type:	South American Hydrology
Date Submitted by the Author:	15-Aug-2016
Complete List of Authors:	Muñoz, Enrique; Universidad Católica de la Santísima Concepción, Department of Civil Engineering; University of Bristol, Water and Environment Engineering Research Group; Centro de Investigación en Biodiversidad y Ambientes Sustentables (CIBAS), Department of Civil Engineering Arumi, Jose Luis; Universidad de Concepcion, Recursos Hidricos Wagener, Thorsten; University of Bristol, Department of Civil Engineering; University of Bristol, Cabot Institute Oyarzún, Ricardo; Universidad de la Serena, Departamento Ingeniería de Minas; Centro de Estudios Avanzados en Zonas Aridas, Parra, Victor; Universidad Católica de la Santísima Concepción, Department of Civil Engineering
Keywords:	Hydrological similarity, Water balance, Mountain hydrology

SCHOLARONE™
Manuscripts

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Unraveling complex hydrogeological processes in Andean basins in south-central Chile: An integrated assessment to understand hydrological dissimilarity

Enrique Muñoz*, Department of Civil Engineering, Universidad Católica de la Santísima Concepción, Alonso de Ribera 2850, Concepción, Chile. Centro de Investigación en Biodiversidad y Ambientes Sustentables (CIBAS), Universidad Católica de la Santísima Concepción, Chile. Research Associate, Water and Environment Engineering Research Group, Department of Civil Engineering, University of Bristol.

José Luis Arumí, CRHIAM Center, Department of Water Resources, Universidad de Concepción, Vicente Méndez 595, Chillán, Chile.

Thorsten Wagener, Department of Civil Engineering, Queens Building, University of Bristol, Bristol, UK. Cabot Institute, University of Bristol, Bristol, UK.

Ricardo Oyarzún, Departamento Ingeniería de Minas, Universidad de La Serena, Benavente 980, La Serena, Chile. Centro de Estudios Avanzados en Zonas Áridas, Av. Raúl Bitrán 1305, La Serena, Chile.

Victor Parra, Department of Civil Engineering, Universidad Católica de la Santísima Concepción, Alonso de Ribera 2850, Concepción, Chile.

Key words: Mountain hydrology, Water balance, Hydrological similarity

* Corresponding author. Phone: +56 41 2345355, email: emunozo@ucsc.cl

Abstract

Groundwater storage, drainage and interbasin water exchange are common hydrological processes, but often difficult to quantify due to a lack of local observations. We present a study of three volcanic mountainous watersheds located in south-central Chile ($\sim 36.9^\circ$ S) in the Chillán volcanic complex (Chillán, Renegado and Diguillín river basins). These are neighboring basins that are similar with respect to the metrics normally available for characterization everywhere (e.g., precipitation, temperature and land cover). In a hydrological sense, similar (proportional) behavior would be expected if these catchments would be characterized with this general information. However, these watersheds show dissimilar behavior when analyzed in detail. The surface water balance does not fit for any of these watersheds individually; however, the water balance of the whole system can be explained by likely interbasin water exchanges. The Renegado River basin has an average annual runoff per unit of area on the order of 60 to 65% less than those of the Diguillín and Chillán rivers, which is contradictory to the hydrological similarity among the basins. To understand the main processes that control streamflow generation, two analyses were performed: i) basin metrics (land cover, geologic, topographic and climatological maps) and hydro-meteorological data analyses and ii) a water balance model approach. The analyses contribute to a plausible explanation for the hydrogeological processes in the system. The soils, topography and geology of the Chillán-Renegado-Diguillín system favor the infiltration and groundwater movements from the Renegado River basin, mainly to the neighboring Diguillín basin. The interbasin water exchanges affect hydrological similarity and explain the differences observed in the hydrological processes of these three apparently similar volcanic basins. The results highlight the complexity of hydrological processes in volcanic mountainous systems and suggest that a simple watershed classification approach

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

based on widely available data is insufficient. Simple local analyses such as specific flow analysis with a review of the geology and morphology can contribute to a better understanding of the hydrology of volcanic mountainous areas.

1.- Introduction

Mountainous watersheds are complex hydrological systems that contribute runoff to lowland areas, provide a favorable temporal redistribution of winter precipitation to spring and summer runoff, and reduce the variability of flows in the adjacent lowlands (Viviroli et al., 2011). This redistribution function of mountainous watersheds is critical for both the ecosystem and the main economic activities in south-central Chile (e.g., hydropower, agriculture, industrial activities and water supply). These activities are highly dependent on water storage in snow, glaciers or groundwater, and therefore on the related water availability during spring and summer (Meza et al., 2012).

Despite the hydrological importance of mountainous watersheds in providing freshwater resources (40% of the world population depends on mountainous regions for water supply, Beniston, 2003), little is known about key hydrological processes in these systems. Processes such as mountain block recharge (Viviroli et al., 2007), surface and groundwater connections (Hughes, 2004) and interbasin groundwater transfer (Zanon et al., 2014) are still rather poorly understood in most mountainous areas around the globe. The intrinsic complexity of recharge processes and the fact that such processes are extremely difficult to observe further contributes to this problem (Ajami et al., 2011; Hartmann et al., 2014). Genereux and Jordan (2006) discuss how documenting and quantifying the long-distance (interbasin) subsurface movement of water between different groundwater systems and the

1
2
3
4 68 influence of groundwater on surface water quantity and quality are of fundamental
5
6 69 significance in hydrogeology and hydrology. Such processes have not been sufficiently
7
8 70 studied in high-elevation basins (Cortés et al., 2011) and are often poorly understood in
9
10 71 places, mainly because they often remain hidden from our current measurement methods
11
12 72 (Wagener et al., 2007) and are often costly to quantify (Zanon et al., 2014). In south-central
13
14 73 Chile, the Chillán-Renegado-Diguillín system (Figure 1) has been studied very little. A first
15
16 74 attempt was recently carried out by Arumí et al. (2014), who used recession flow analysis
17
18 75 and stable isotope analysis to estimate groundwater storage trends in the upper part of the
19
20 76 Diguillín basin. They concluded that the Diguillín River is supported by two main groups
21
22 77 of springs, one at the headwaters, connected to a volcanic aquifer, and one downstream of
23
24 78 the junction with its main tributary (the Renegado River). Complementarily, Naranjo et al.
25
26 79 (2008) described that the Chillán volcanic complex presents several small thermal and cold
27
28 80 springs distributed along the perimeter of the volcanic complex, such as those described by
29
30 81 Arumí et al. (2014).
31
32
33
34
35

36
37 82 Within this context, this paper goes further in analyzing and integrating different sources of
38
39 83 information to i) understand the groundwater connection and storage-runoff process and ii)
40
41 84 estimate the interbasin flow exchange between Andean basins in south-central Chile, taking
42
43 85 as a case study the system of the Chillán-Renegado-Diguillín river basins. In order to
44
45 86 achieve these goals, we used an approach based on i) a basin metrics (land cover, geologic,
46
47 87 topographic and climatological maps) and hydro-meteorological data analyses and ii) a
48
49 88 water balance model analysis.
50
51
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

89 **2.- Study Area and Data**

90 The study area includes three neighboring volcanic mountainous watersheds located in
91 south-central Chile at the hillslope of the Chillán volcanic complex: the Diguillín River
92 (207 km²), Renegado River (127 km²) and Chillán River (210 km²) basins (Figure 1.b).

93 To derive the basin metrics, climatological, land cover, morphological and geologic maps
94 and an aerial picture of the study area were constructed. The land cover map (Figure 1.a)
95 was constructed based on the 300 m resolution map presented by Bontemps et al. (2013).
96 The Bontemps et al. (2013) land cover map is derived from global time series acquired by
97 the Envisat MERIS Full and Reduced Resolution dataset (FR and RR, respectively) and
98 from SPOT-Vegetation (SPOT-VGT) sensors. The spatial resolution of the source data
99 varies from 300 to 1000 m and the time periods available lie within the years 1998 to 2012.
100 Complementarily, an aerial picture of the watersheds based on ESRI World Imagery
101 (Figure 1.b), a terrain map based on the Advanced Spaceborne Thermal Emission and
102 Reflection Radiometer (ASTER) of 1 arc-second satellite stereo images (Figure 1.c) and a
103 geologic map (Figure 1.d) extracted from Sernageomin (2003) (scale 1:1.000.000) were
104 constructed. The climatological maps constructed use mean annual precipitation (Figure
105 1.e) and temperature (Figure 1.f). Additionally, several metrics were included in Figure 1 to
106 further characteristics the basins.

107 Within and close to the study area there are only three rain gauges (Figure 1.b), all of them
108 located at low altitudes. Therefore, to estimate precipitation and temperature values for
109 each basin and better represent its spatial distribution within the study area, AgMERRA
110 datasets of 0.25° resolution (~25 km) for the 1980-2010 period were obtained (Ruane et al.,
111 2015). AgMERRA datasets provide daily, high-resolution and continuous meteorological

series over the 1980-2010 period. These datasets combine daily resolution data from retrospective analyses (the Modern-Era Retrospective Analysis for Research and Applications) from NASA (Rienecker et al., 2011) with in situ and remotely-sensed observational datasets for temperature, precipitation, and solar radiation (Ruane et al., 2015). The AgMERRA datasets exhibited negative bias in precipitation (~30 to 50% less) for the study area (Ruane et al., 2015). To address this issue, they were amplified to achieve the mean annual total estimated for the study area using the isohyets method and annual precipitation isohyets published by DGA (1987). Finally, in order to analyze the runoff generation processes in the basins, monthly streamflow data were obtained from the Renegado at Invernada (RI), Diguillín at San Lorenzo (DSL) and Chillán at Esperanza stations (Figure 1.b). Although RI and DSL have more recent records, CE does not have data beyond 1994, since the gauging station was destroyed by a flood in 1995. Therefore, the common period of 1980-1994 was used in order to use a comparative period for the analyses.

Figure 1.a shows that the land cover of the three basins is very similar (cover distribution percentages are included in the map). The three basins are mostly covered by evergreen and semi-deciduous forests (Figueroa et al., 2007) (~78% in Chillán and ~65% in Diguillín and Renegado) and to a lesser extent by forest-shrubland-grassland (~17% in Chillán and ~30% in Diguillín and Renegado). In addition, a small portion of the Chillán River basin (~1.5 km²) is covered by permanent snow and ice associated with the glacier documented by Zenteno (2009) and Rivera and Bown (2013).

The elevation map (Figure 1.c) shows that the three basins have the same maximum elevation, but that their elevation distributions differ. The elevations of the Renegado River

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

basin (median elevation of ~1550 masl) are concentrated slightly above those of the Diguillín (median elevation of ~1450 masl), while both are above those of the Chillán River basin (median elevation of ~1291 masl). The elevation ranges of the Diguillín (min/max 700/3171 masl) and Renegado (min/max 825/3180 masl) river basins are similar, while that of the Chillán River basin, which has a lower minimum elevation, is slightly wider (min/max 423/3188 masl). In addition, all of them present the highest elevations at their eastern limits (Chillán Volcano) and slopes in a W-E direction.

Most of the area of the watersheds is composed of units of volcanic origin with the common characteristic of having been formed by lavas cooled outside of the volcano, resulting in highly fractured soil layers deposited among the basins. The geologic map (Figure 1.d) shows six main deposits. Four of them are volcanic deposits related to the Chillán volcanic complex, which cover 84% of the total area of the system. The remaining surface is covered by granodiorites and diorites. The Renegado River basin has the lowest proportion of volcanic deposits coverage (75% of its total area) and the Diguillín River basin has the highest (90% of its total area). In the upper third of the Renegado River basin, at its southern edge, a granodiorite-diorite deposit (commonly an impermeable layer) is found. Such deposits are also found at the headwaters of the Diguillín River.

Frontal systems produce most of the precipitation from deep stratiform clouds that develop along warm and cold fronts, covering large areas (usually larger than the study area) (Garreaud et al., 2009). Additionally, winds and frontal systems move in a W-E direction. Therefore, the spatial variability of precipitation within the study area (Figure 1.e) is highly longitudinal (in terms of amounts) due to the increase in precipitation caused by orography

(Garreaud et al., 2009), while latitudinal variations are mostly noticed at larger (e.g., regional) scales.

According to the corrected AgMERRA datasets, the mean annual precipitation of the system is around 2283 mm while the mean annual air temperature is 10.5 °C, ranging from 4.4 °C in the coldest month of winter (June) to 18.0 °C in the hottest month of summer (January). The Chillán River basin shows the lowest annual precipitation (2207 mm against 2371 and 2308 mm for Renegado and Diguillín river basins, respectively) although precipitation is practically the same across the system. Regarding the temperature distribution, the Chillán, Renegado and Diguillín river basins present mean annual temperatures of 10.2, 9.4 and 9.2 °C, respectively.

After an initial review of basin maps and metrics (Figure 1), the basins of the Chillán-Renegado-Diguillín system would typically be classified as similar and, therefore, in a hydrological sense, it is reasonable to expect that they would “behave similarly” (Winter, 2001) and that main hydrological processes would be equivalent or proportional.

Complementarily, to further investigate the behavior of the basins, the monthly runoff per unit of area for each basin (q), so-called specific flow were calculated and compared among basins. Results related are shown in section 4.1.

3.- Model and Methods

3.1 Water Balance Model

To complement the previous analyses, an approach based on a water balance was used. Each basin independently and the whole system of three basins were analyzed in order to

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

estimate how much water is “gained” or “lost” by each basin. Considering that the modeling approach seeks to identify potential interbasin groundwater flows and that the study area, like most of the Andes, is a data-sparse area (Viviroli et al., 2011), the lumped water balance model presented in Muñoz (2010) and Muñoz et al. (2014) was used (Figure 2).

The model includes a rainfall-runoff component that considers the watershed as a double storage system: unsaturated (US) and saturated (SS). US represents the water stored in the unsaturated soil layer as soil moisture and SS represents the water that covers the saturated soil layer. The model needs two inputs: precipitation (PM) and potential evapotranspiration (PET). The model output is the total runoff (ETOT) at the watershed outlet, and includes both the groundwater contribution (ES) and surface runoff (EI), the amounts of which are calculated through six calibration parameters, plus one for the precipitation modification.

Additionally, the model includes a snowmelt-runoff component that calculates the snowfall (Psnow) based on precipitation above the 0 degree (base temperature at which liquid precipitation starts) isotherm falling as snow. Psnow is stored in the snow storage system (SN), from which the melting calculations are performed based on the concept of the degree-day method (Rango and Martinec, 1995). Thus, the potential melting (PSP) is estimated, and then based on the snow stored, the actual melting (PS) is calculated. Then PS is distributed into the rainfall-runoff model through the factor of snowmelt transference F. Additionally, to consider the sub-monthly variability of the air temperature in the basin, a factor of minimum snowmelt (DM), which is defined as a fraction of the snow stored in the basin, is incorporated into the model. Table 1 presents a brief description of the model parameters, their influence on the model and the regular range considered for parameter

estimation. A further description of model design and equations can be found in Muñoz (2010) and Muñoz et al. (2014).

As forcing, the model requires precipitation and potential evapotranspiration. The corrected AgMERRA datasets were used to estimate basin precipitation and the Thornthwaite method (Thornthwaite, 1948) and AgMERRA temperature series were used to estimate basin potential evapotranspiration. The Inverse Distance Weighting method was used to estimate representative values for each basin.

3.2 Monte Carlo Framework

To ensure the closure of the water balance, the model includes a scale factor (A) that permits the inputs of water (precipitation) in the Muñoz (2010) model to be increased or decreased. In order to estimate potential interbasin water exchanges, factor A was estimated for each basin and for the system. Considering that around 0.75% of the area of the Chillán basin is covered by permanent snow (Figure 1.c) and, moreover, the lack of measurements and knowledge of the characteristics of the glacier located at the headwaters of the Chillán River basin, the water balance approach did not include the glacier melting contributions for the modeling stage of either the system or the Chillán River basin model.

An approach based on Monte Carlo simulations and regional sensitivity analysis (Wagener et al., 2001) was first used to estimate values of A. A was defined as the median of the best 10% models according to a predefined objective function (the Runoff Coefficient Error – ROCE). Based on prior experiences (Muñoz et al., 2014, Pinto, 2014, Toledo et al., 2015), 10,000 simulations were performed using randomly selected parameter values (sampled according to a uniform distribution) within the initial range defined in Table 1.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Aimed at first ensuring the closure of the water balance, ROCE was used as objective function (Eq.1). ROCE captures the overall accuracy of the water balance i) by combining the flows into one characteristic hydrological descriptor, the mean annual runoff coefficient (defined as Q/P), and ii) by minimizing the absolute difference between total measured and simulated runoff. The absolute error in the runoff coefficient is then calculated as follows, where the mean annual flow \bar{Q} and the mean annual precipitation \bar{P} are used for the simulated (s) or observed (o) flows (van Werkhoven et al., 2009),

$$ROCE = \text{abs} \left(\frac{\bar{Q}_s}{\bar{P}} - \frac{\bar{Q}_o}{\bar{P}} \right) \quad [\text{Eq.1}]$$

After defining A (using ROCE), 10,000 new simulations were performed and parameter values were estimated as the median of the best 10% behavioral models. To define the behavioral models, the Nash-Sutcliffe Efficiency (NSE) was used, where models with NSE values greater than 0.75 were considered as behavioral (Van Liew et al. (2005) classified models with NSE over 0.75 as “good”).

In order to demonstrate the representativeness of the models and results, two periods with available common data among basins were considered to carry out the analyses. Period 1, from 1980 to 1987 (P1), and Period 2, from 1988 to 1994 (P2), were defined. In addition, a cross validation was performed, i.e., P1 was used for calibration and P2 for validation, and then P2 was used for calibration and P1 for validation.

4.- Results

4.1 Specific Flow Analysis

243 To analyze the behavior of the basins, the annual precipitation distribution over the study
244 area and the monthly runoff per unit of area for each basin (q), so-called specific flow, were
245 plotted (Figure 3). Figure 3 shows that the Renegado River basin, which is located between
246 the Chillán and Diguillín rivers, yields much less specific flow (about 2 to 4 times less)
247 than its neighboring basins, even though they are in close proximity, appear to be similar
248 and, moreover, are driven by similar climatic patterns (Garreaud et al., 2009, Pinto, 2014).
249 Additionally, the Diguillín River shows larger q values than the Chillán River for most of
250 the year (about 1 to 1.4 times more between April and November), although this
251 relationship is inverted in summer, when the Chillán River basin shows larger q values (1.1
252 to 1.4 times) than the Diguillín River basin (Figure 3.b).

253 We expect basins with similar metrics to have similar runoff generation processes (Reed et
254 al., 2006, Wagener et al., 2007); and therefore, similar specific discharge curves should be
255 expected. However, significant differences among basins can be noticed here. The specific
256 discharge curves provide insights into the main characteristics and the dominating
257 hydrological processes of the basins (and the system) that allow us to obtain and analyze
258 complementary information in order to redefine our conceptual model of the system.

259 A first line of evidence that may explain the observed behavior is related to aspects of
260 geology and morphology. The geology of the upper section of the Diguillín watershed is
261 described in detail by Dixon et al. (1999), Sernageomin (2003) and Naranjo et al. (2008).
262 They explain the strong influence of the volcanic processes associated with the Chillán
263 volcanic complex, which is composed of several types of structures created by different
264 processes that have occurred over approximately 650 million years. They found mostly

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

265 lavas of high permeability caused by fast cooling processes with consequent fracturing in
266 rocks.

267 Naranjo et al., (2008) described most of the lavas that filled the Renegado basin valley,
268 highlighting three formations: i) Los Pincheira lavas: deposited in Middle Pleistocene,
269 these lavas covered the Renegado valley by crossing a glacier and thereby forming large
270 walls (very steep hills over 100 m tall), which give the valley a U-shape. At the lower
271 border of the glacier, the lava flow opened and the walls disappeared; ii) Diguillín Lavas:
272 deposited in Middle Pleistocene after the Los Pincheira lavas, these lavas descended
273 through the Renegado valley but were blocked by the former and forced to deviate to the
274 Diguillín River, forming the surface connection with that river and defining the western
275 edge of the Renegado River basin; and iii) Atacalco lavas: these lavas were deposited in the
276 Middle-Upper Pleistocene and filled the Renegado valley. They accumulated in the
277 Atacalco area (upper north Diguillín basin) and laterally covered both the Los Pincheira
278 and Diguillín lavas. All these lavas are characterized by a dense jointing, favoring the fast
279 movement of groundwater.

280 The volcanic structures that cover most of the system area were found to be highly
281 permeable. Navarro (2015) measured an infiltration capacity of the soil of 200 mm/hr at the
282 headwaters of the Renegado River basin. In addition, the described deposition sequence
283 caused the Renegado valley to be developed at higher altitudes than the Diguillín, and at
284 elevations similar to those of the Chillán River basin (Figure 4). This situation, combined
285 with permeable and fractured soil layers composed of lava deposits, favors the rapid
286 infiltration process but also gravitational movements of groundwater. Therefore,
287 groundwater likely moves from the Renegado to the Diguillín River basin gravitationally.

These fast infiltration and interbasin groundwater movement processes would explain both why the Renegado River basin does not have significant surface runoff and the results observed from the specific flow analysis.

Complementarily, Masiokas et al. (2009) described that the glacier located at the headwaters of the Chillán River basin has been reduced over the last ~150 years from 30 to 6 km². This reduction might explain the higher specific flows (in comparison with the Diguillín and Renegado) observed during summer (Figure 3).

4.2 Watershed Model Analysis

Table 2 shows the results of the modeling approach (model parameters) for each basin modeled independently and for the system as a whole. Table 2 shows that factor A, which ensures the closure of the water balance, is markedly different among the basins. Analyzing each basin as an independent system, it is observed that for the Chillán and Diguillín river basins, precipitation must be amplified by ~24–32% in order to close the water balance. On the other hand, for the Renegado River basin, the results are the opposite, as precipitation must be reduced by ~35–40% to achieve closure of the water balance. Additionally, if the Chillán-Renegado-Diguillín system is assumed as a closed unit, precipitation must be increased by ~14–20% (Table 2).

To estimate interbasin groundwater flows, the mean annual precipitation of each basin and of the system was multiplied by the mean value of A (considering the two calibration periods). As result, a total of 2661 mm is received by the system while totals of 2802, 1487 and 3015 mm are received by the Chillán, Renegado and Diguillín basins, respectively. Based on the differences with the system, and considering the proportions of volume to basin area, the Diguillín and Chillán basins receive 355 and 141 mm, respectively, from the

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Renegado River basin. Meanwhile, the Renegado River basin loses this amount of water plus 363 mm that goes to neither the Chillán nor the Diguillín River (upstream of the gauge station). This water probably goes downstream to the junction of the Renegado and Diguillín rivers to the springs documented by Arumí et al. (2014).

It is important to point out that the modeling stage did not include glacier melt contributions; therefore, the interbasin groundwater flows should actually be slightly smaller for the Chillán River basin and higher for the Diguillín River downstream of the junction with the Renegado River.

Table 2 shows that the highest C_k values were obtained for the Renegado River basin, suggesting that its groundwater system empties faster and thus varies more throughout the year than those of the Diguillín and Chillán basins. On the other hand, the lowest C_k values were obtained for the Chillán basin, indicating that it is the most stable groundwater system among the basins studied. C_k values of the Renegado River basin indicate that its groundwater system empties nearly twice as fast as the whole system. In addition, the C_k values for the Diguillín basin suggest that it empties slightly faster (1.2 to 1.3 times) than the whole system, but that it also has more variability, which may be influenced by an interbasin groundwater flow from the Renegado to the Diguillín basin.

Regarding the maximum surface runoff coefficient (C_{max}), the Diguillín basin shows the highest values and the Renegado basin the lowest. These results suggest that the Diguillín River basin tends to be more saturated and therefore higher runoff rates can be achieved. Moreover, they suggest that the Renegado River basin tends to infiltrate more water; as a consequence, the surface runoff is reduced. For the Chillán basin, C_{max} values slightly lower than those of the total system are observed. This result may be influenced by the

334 morphology of the basin, where the lower third of the Chillán basin is flatter (in comparison
335 to the rest of the study area), favoring infiltration over surface runoff. In addition, the
336 Diguillín and Renegado basins show higher and lower C_{\max} values than the total system
337 respectively, suggesting that i) the Diguillín/Renegado basin generates more/less surface
338 runoff than the average of the study area (the system), and ii) in the Renegado River basin,
339 the infiltration process predominates in streamflow generation.

340 5.- Discussion

341 An initial (broad) review of the metrics of the three basins suggests that they are likely to
342 be similar. They are neighboring basins with similar climatic patterns and land cover and
343 the aerial view showed similar qualitative characteristics. In addition, the geology, from a
344 broad view can also be considered to be similar for the three basins, because it is dominated
345 by permeable volcanic material. Moreover, the effect of the glacier flows in summer can be
346 assumed to be negligible due to the small size observed in the land cover map ($\sim 1.5 \text{ km}^2$,
347 which is around 0.75% of the area of the Chillán basin). Therefore, the three basins should
348 behave similarly and their hydrological processes are expected to be equivalent.

349 However, the review of the hydrological data showed that the basins behaved dissimilarly.
350 The Renegado River basin exhibited less specific flow than its neighboring basins,
351 suggesting interbasin water exchanges (Renegado \rightarrow Chillán and Renegado \rightarrow Diguillín). In
352 addition, a glacier melting process might be considered for the Chillán River basin after
353 observing the specific flows in summer plus the glacier reductions documented by Zenteno
354 (2009). Such reductions would explain the high specific flows observed in summer for the
355 Chillán River basin, while larger contributions from the Renegado to the Diguillín would

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

356 explain the higher q values observed for the Diguillín River basin during the course of the
357 year.

358 The foregoing is in agreement with the modeling approach results. Since the orography
359 produces an increase in precipitation with altitude in the Andes (Garreaud et al., 2009), and
360 considering that the AgMERRA datasets include data from rain gauges (which are only
361 located at low altitudes), values of A higher than one might be expected. However, for the
362 Renegado River basin, contradictory results were obtained.

363 Although these results may initially be opposite to expectations, they suggest that the
364 Renegado River basin exchanges water with both the Diguillín and Chillán basins. As the
365 Renegado River basin “loses” water, the Diguillín and Chillán basins “gain” it, which
366 explains the higher and lower values for each basin than those estimated for the combined
367 system. These results are consistent with the springs described by Arumí et al. (2014) in the
368 upper third of the Diguillín River basin and downstream of the junction with the Renegado
369 River. The geologic map indicates that soil layers in the Renegado River basin are highly
370 permeable, and the morphologic map shows differences in elevations among rivers (Figure
371 4). Therefore, gravitational movement of groundwater from the Renegado River to both the
372 Chillán and Diguillín river basins is plausible.

373 The connections described are in agreement with the geomorphological information and are
374 consistent with the water balance approach. Regarding the geology, permeable and
375 fractured soil layers favor rapid infiltration and gravitational water movements from the
376 Renegado River basin. Moreover, the deposition sequence caused the Renegado valley to
377 be formed at higher altitudes than the Diguillín and at elevations similar to the Chillán

1
2
3 378 River basin (see Figure 4). Therefore, it would be expected that more water is transferred to
4
5 379 the Diguillín River in comparison to the Chillán River basin.
6
7

8 380 Tóth (1963; 1999) and Sophocleous (2002) have described the importance of topographic
9
10 381 relief for local groundwater flows, highlighting that the higher the topographic relief, the
11
12 382 greater the importance of local groundwater systems. Interbasin flow can occur even
13
14 383 without geological heterogeneity in such circumstances. Therefore, in the Chillán-
15
16 384 Renegado-Diguillín system, topographic relief could play an important role in water
17
18 385 redistribution, as has been suggested by the specific flow analysis.
19
20
21
22

23 386 Besides the Renegado to Diguillín interbasin water exchanges identified upstream of the
24
25 387 Diguillín at San Lorenzo stream gauge station, another exchange of similar magnitude
26
27 388 downstream of the station was identified during the modeling stage, reinforcing the
28
29 389 observations by Naranjo et al. (2008) and Arumí et al. (2014). A modified conceptual
30
31 390 representation of the complete system after including such connections and the main basin
32
33 391 processes is shown in Figure 5.
34
35
36
37

38 392 The finding of interbasin groundwater transfer has important implications for hydrology,
39
40 393 ecology and land-water management. For the Chillán-Renegado-Diguillín system, for
41
42 394 example, volcanic processes conditioned the geology and morphology, forming fractured
43
44 395 and permeable soil layers, but also forming valleys at different elevations within a few
45
46 396 kilometers. These conditions favor interbasin exchange and help to explain the differences
47
48 397 observed in the hydrology in three apparently similar basins. Interbasin groundwater flow
49
50 398 diminishes surface water discharge from basins in which interbasin groundwater flow
51
52 399 originates and increases discharge from those receiving this water (Genereux and Jordan,
53
54 400 2006). This phenomenon coincides with the observed behavior in the Chillán-Renegado-
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Diguillín system. Along the same lines, Zanon et al. (2014), Montgomery et al. (2003) and Langman and Ellis (2013) have found similar patterns in different sites around the globe, all of which were located in volcanic mountainous areas.

Zanon et al. (2014) showed that two nearly identical or at least very similar neighboring basins (similar in precipitation, temperature, vegetation, soils, geology and topography) in the Central Cordillera of Costa Rica proved to have markedly different behavior. They found interbasin groundwater flow in which one basin (Arboleda River basin) was receiving a large input of groundwater from a neighboring basin (Toscanazo River basin). In addition, the authors describe that these basins are located in a volcanic area with a combination of high-permeability lava beds and lower-permeability ignimbrites and pyroclastics. Montgomery et al. (2003) studied the interbasin groundwater movement in basins of the Chilean Altiplano (in northern Chile), attributing the interbasin water movements to the geological formations and fractured volcanic rock aquifers. In the same way, Langman and Ellis (2013) found in the southern Rio Grande Valley in the southwestern USA that in a volcanic area with permeable layers and geological faults, deep groundwater interbasin connections would be allowed. Larned et al. (2015) stated that streams in tectonically active volcanic landscapes are characterized by complex groundwater-surface water interactions that include interbasin transfers of groundwater. Similar to our study, the investigations described above attributed the interbasin water exchanges and basin dissimilarities in runoff to the volcanic deposits and geological (and relief-related) formations. Therefore, for volcanic mountainous watersheds, complex groundwater interactions across neighboring basins need to be expected.

Hydrological similarity is a concept widely used by hydrological practitioners for estimating available water resources or the probability for hydrological extremes. In particular, it is the basis for runoff predictions in ungauged basins, to assist in the understanding of hydrological processes or to make hydrological predictions (Blöschl et al., 2013; Wagener et al., 2007). In volcanic mountainous watersheds, geology and relief have been shown to be key aspects to consider before assuming hydrological similarity. A good understanding of groundwater movement in adjacent small basins makes possible an accurate representation of the motion of groundwater within the large basin that they form (Tóth, 1963). Therefore, identifying such movements could lead to better water management and planning at basin scale. However, most volcanic mountainous watersheds are difficult to access; therefore, hydrological, climatic and geological information is usually non-existent or not as detailed as desired. Mountain watersheds are essential for supplying and supporting the water needs of adjacent lowlands (Viviroli et al., 2007); additional efforts are therefore needed to adequately estimate complex hydrological processes in such watersheds. Based on the research presented here, a comparison of the specific discharge of neighboring basins would provide key insights into potential interbasin exchanges, contributing to a better understanding of complex mountainous hydrological systems.

6.- Conclusions

This study addressed the issue of hydrological dissimilarity in neighboring volcanic mountainous basins located in the Andean region of south-central Chile. Although the basins had apparently similar characteristics, their hydrological behavior proved to be

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

markedly different. This is explained by the special geological and topography-related characteristics of the volcanic complex where the basins are located, which determine the transfer of water from the Renegado River basin to Chillán and Diguillín river basins. These results highlight the complexity of hydrological processes in volcanic basins of mountainous areas, making it necessary to consider additional efforts to understand the main processes in such systems. Further analyses, such as specific flow analysis, would help us better understand and, moreover, identify potential interactions. It also suggests that practical approaches for hydrologic predictions based on similarity principles as currently applied in the region are insufficient, and that deeper hydrological understanding than currently utilized needs to be embedded to achieve robust estimates of likely hydrological behavior.

7.- Acknowledgments

The authors wish to express their gratitude for the support given by the Chilean Scientific Council (CONICYT) through Fondecyt projects 11121287, 1110298, and 1150587 and Conicyt/Fondap 15130015.

References

- Ajami H, Troch P, Maddock III T, Meixner T, Eastoe C. 2011. Quantifying mountain block recharge by means of catchment-scale storage-discharge relationships. *Water Resources Research* **47**: W04504.
- Arumí JL, Oyarzún R, Muñoz E, Rivera, D. 2014. Caracterización de dos grupos de manantiales en el río Diguillin, Chile. *Water Technology and Sciences* **5** (6): 151-158.
- Beniston M. 2003. Climatic change in mountain regions: a review of possible impacts. *Climatic Change* **59**: 5–31.
- Blöschl G, Sivapalan M, Wagener T, Viglione A, Savenije H. 2013. Runoff Prediction in Ungauged Basins. *Synthesis across Processes, Places and Scales*. Cambridge University press.
- Bontemps S, Defourny P, Radoux J, Van Bogaert E, Lamarche C, Achard F, Mayaux P, Boettcher M, Brockmann C, Kirches G, Zülke M, Kalogirou V, Arino O. 2013. Consistent Global Land Cover Maps for Climate Modeling Communities: Current Achievements of the ESA's Land Cover CCI. Proceedings of the ESA Living Planet Symposium, Edimburg.
- Cortés G, Vargas X, McPhee J. 2011. Climatic sensitivity of streamflow timing in the extratropical western Andes Cordillera. *Journal of Hydrology* **405**: 93-109.
- DGA. 1987. Balance hídrico de Chile. Dirección General de Aguas, Ministerio de Obras Públicas, Santiago, Chile.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

481 Dixon H, Mick J, Murphy D, Sparks S, Chávez R, Naranjo J, Dunkley P, Young P, Gilbert
482 J, Pringle M. 1999. The geology of Nevados de Chillán volcano, Chile. *Revista Geológica
483 de Chile* **26** (2): 227-253.

484 Figueroa R, Palma A, Ruiz V, Niell X. 2007. Análisis comparativo de índices bióticos
485 utilizados en la evaluación de las aguas en un río mediterráneo de Chile: río Chillán, VIII
486 Región. *Revista Chilena de Historia Natural* **80**: 225-242.

487 Garreaud D, Vuille M, Compagnucci R, Marengo, J. 2009. Present-day South American
488 climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* **281** (3-4): 180-195.

489 Genereux D, Jordan M. 2006. Interbasin groundwater flow and groundwater interaction
490 with surface water in a lowland rainforest, Costa Rica. A review. *Journal of Hydrology* **320**
491 (3-4): 385-399.

492 Hartmann A, Goldscheider N, Wagener T, Lange J, Weiler M. 2014. Karst water resources
493 in a changing world: Review of hydrological modeling approaches. *Reviews of Geophysics*
494 **52** (3): 218-242.

495 Hughes D. 2004. Incorporating groundwater recharge and discharge functions into an
496 existing monthly rainfall–runoff model. *Hydrology and Earth System Sciences* **49** (2): 297-
497 311.

498 Langman JB, Ellis AS. 2013. Geochemical indicators of interbasin groundwater flow
499 within the southern Rio Grande Valley, southwestern USA. *Environmental earth sciences*
500 **68** (5): 1285-1303.

501 Larned ST, Gooseff MN, Packman AI, Rugel K, Wondzell SM. 2015. Groundwater–
502 surface-water interactions: current research directions. *Freshwater Science* **34** (1): 92-98.

- 503 Masiokas MH, Rivera A, Espizua LE, Villalba R, Delgado S, Aravena JC. 2009. Glacier
504 fluctuations in extratropical South America during the past 1000 years. *Palaeogeography,*
505 *Palaeoclimatology, Palaeoecology* **281** (3): 242-268.
- 506 Meza F, Wilks D, Gurovich L, Bambach N. 2012. Impacts of Climate Change on Irrigated
507 Agriculture in the Maipo Basin, Chile: Reliability of Water Rights and Changes in the
508 Demand for Irrigation. *Journal of Water Resources Planning and Management* **138** (5):
509 421-430.
- 510 Montgomery EL, Rosko MJ, Castro SO, Keller BR, Bevacqua PS. 2003. Interbasin
511 underflow between closed Altiplano Basins in Chile. *Groundwater* **41** (4): 523-531.
- 512 Muñoz E. 2010. Desarrollo de un modelo hidrológico como herramienta de apoyo para la
513 gestión del agua. Aplicación a la cuenca del río Laja, Chile (Development of a hydrological
514 model as a support tool for water management. Application to the basin of the Laja river,
515 Chile). Thesis, Departamento de Ciencias y Técnicas del Agua y del Medio Ambiente.
516 Universidad de Cantabria, España.
- 517 Muñoz E, Rivera D, Vergara F, Tume P, Arumi JL. 2014. Identifiability analysis: towards
518 constrained equifinality and reduced uncertainty in a conceptual model. *Hydrological*
519 *Sciences Journal* **59** (9): 1690-1703.
- 520 Naranjo J, Gilbert J, Sparks R. 2008. *Geología del complejo volcánico Nevados de Chillán,*
521 *Región del Biobío (Geology of the volcanic complex Nevados del Chillán)*. Carta Geológica
522 de Chile, Serie Geología Básica 114, Servicio Nacional de Geología y Minería, Chile.
- 523 Navarro L. 2015. Estudio de caso: Análisis edafogeoambiental de la zona de Las Trancas
524 Chillán. Thesis, Universidad de Concepción, Chile.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

Philippi A. 1863. Exkursion nach den Bädern und dem Neuen Vulkan von Chillán in Chile, in Spätsommer 1862 gemacht. *Petermann's Geographische Mittheilungen*. 241-257.

Pinto E. 2014. Análisis de las dinámicas hidrológicas de la cuenca del río Diguillín, Civil Engineering Thesis, Universidad Católica de la Santísima Concepción, Chile. 101 p.

Rango A, Martinec J. 1995. Revisting the degree-day method for snowmelt computations. *Journal of American Water Resources Association* **31** (4): 657-669.

Reed PM, Brooks RP, Davis KJ, DeWalle DR, Dressler KA, Duffy CJ, Yarnal B. 2006. Bridging river basin scales and processes to assess human-climate impacts and the terrestrial hydrologic system. *Water Resources Research* **42** (7).

Rienecker MM, Suarez MJ, Gelaro D, Todling R, Bacmeister J, Liu E, Bosilovich MG, Schubert SD, Takacs L, Kim G-K, Bloom S, Chen J, Collins D, Conaty A, da Silva A, GuW, Joiner J, Koster RD, Lucchesi R, MolodA,Owens T, Pawson S, Pegion P,RedderCR,ReichleR,Robertson FR, Ruddick AG, Sienkiewicz M, Woollen J. 2011. MERRA - NASA's Modern-Era Retrospective Analysis for Research and Applications. *Journal of Climate* 24: 3624–3648. DOI: 10.1175/JCLI-D-11-00015.

Rivera A, Bown F. 2013. Recent glacier variations on active ice capped volcanoes in the Southern Volcanic Zone (37° – 46°S), Chilean Andes. *Journal of South American Earth Sciences* **45**: 345-356.

Ruane AC, Goldberg R, Chryssanthacopoulos J. 2015. AgMIP climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. *Agricultural and Forest Meteorology* **200**: 233-248.

- 1
2
3 546 Sernageomin, 2003. Mapa Geológico de Chile: versión digital. Servicio Nacional de
4
5 547 Geología y Minería. *Publicación Geológica Digital* 4.
6
7
8 548 Sophocleous M. 2002. Interactions between groundwater and surface water: the state of the
9
10 549 science. *Hydrogeology Journal* 10: 52–67 DOI 10.1007/s10040-001-0170-8.
11
12
13 550 Thornthwaite C. 1948. An approach toward a rational classification of climate.
14
15 551 *Geographical Review* 38 (1): 55-94.
16
17
18 552 Toledo C, Muñoz E, Zambrano-Bigiarini M. 2015. Comparison of Stationary and Dynamic
19
20 553 Conceptual Models in a Mountainous and Data-Sparse Catchment in the South-Central
21
22 554 Chilean Andes. *Advances in Meteorology*, 2015:526158. DOI:10.1155/2015/526158.
23
24
25 555 Tóth J. 1963. A theoretical analysis of groundwater flow in small drainage basins. *Journal*
26
27 556 *of Geophysical Research* 68 (16): 4795–4812.
28
29
30 557 Tóth J. 1999. Groundwater as a geologic agent: An overview of the causes, processes, and
31
32 558 manifestations. *Hydrogeology Journal* 7: 1-14.
33
34
35 559 Van Liew M, Arnold J, Bosch D. 2005. Problems and potential of autocalibrating a
36
37 560 hydrologic model. *Transactions of the ASAE* 48(3): 1025–1040.
38
39
40 561 Van Werkhoven K, Wagener T, Reed P, Tang Y. 2009. Sensitivity-guided reduction of
41
42 562 parametric dimensionality for multi-objective calibration of watershed models. *Advances in*
43
44 563 *Water Resources* 32: 1154–1169.
45
46
47 564 Viviroli D, Durr HH, Messerli B, Meybeck M, Weingartner R. 2007. Mountains of the
48
49 565 world, water towers for humanity: Typology, mapping, and global significance. *Water*
50
51 566 *Resources Research* 43: W07447 DOI:10.1029/2006WR005653.
52
53
54
55
56
57
58
59
60

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

567 Viviroli D, Archer DR, Buytaert W, Fowler HJ, Greenwood GB, Hamlet AF, Huang Y,
568 Koboltschnig G, Litaor MI, López-Moreno JI, Lorentz S, Schädler B, Schreier H,
569 Schwaiger K, Vuille M, Woods R. 2011. Climate change and mountain water resources:
570 overview and recommendations for research, management and policy. *Hydrology and*
571 *Earth System Sciences* **15**: 471-504.

572 Wagener T, Boyle DP, Lees MJ, Wheater HS, Gupta HV, Sorooshian S. 2001. A
573 framework for development and application of hydrological models. *Hydrology and Earth*
574 *System Sciences* **5** (1): 13-26.

575 Wagener T, Sivapalan M, Troch P, Woods R. 2007. Catchment Classification and
576 Hydrologic Similarity. *Geography Compass* **1** (4): 901-931.

577 Winter TC. 2001. The concept of hydrologic landscapes. *Journal of the American Water*
578 *Resources Association* **37**: 335–349.

579 Zanon C, Genereux D, Oberbauer S. 2014. Use of a watershed hydrologic model to
580 estimate interbasin groundwater flow in a Costa Rican rainforest. *Hydrological Processes*.
581 **28**: 3670–3680.

582 Zenteno P. 2009. Variaciones recientes de los glaciares en la zona centro sur de Chile y su
583 relación con los cambios climáticos y la actividad volcánica. Thesis, Facultad de
584 Arquitectura y Urbanismo. Universidad de Chile, Chile.

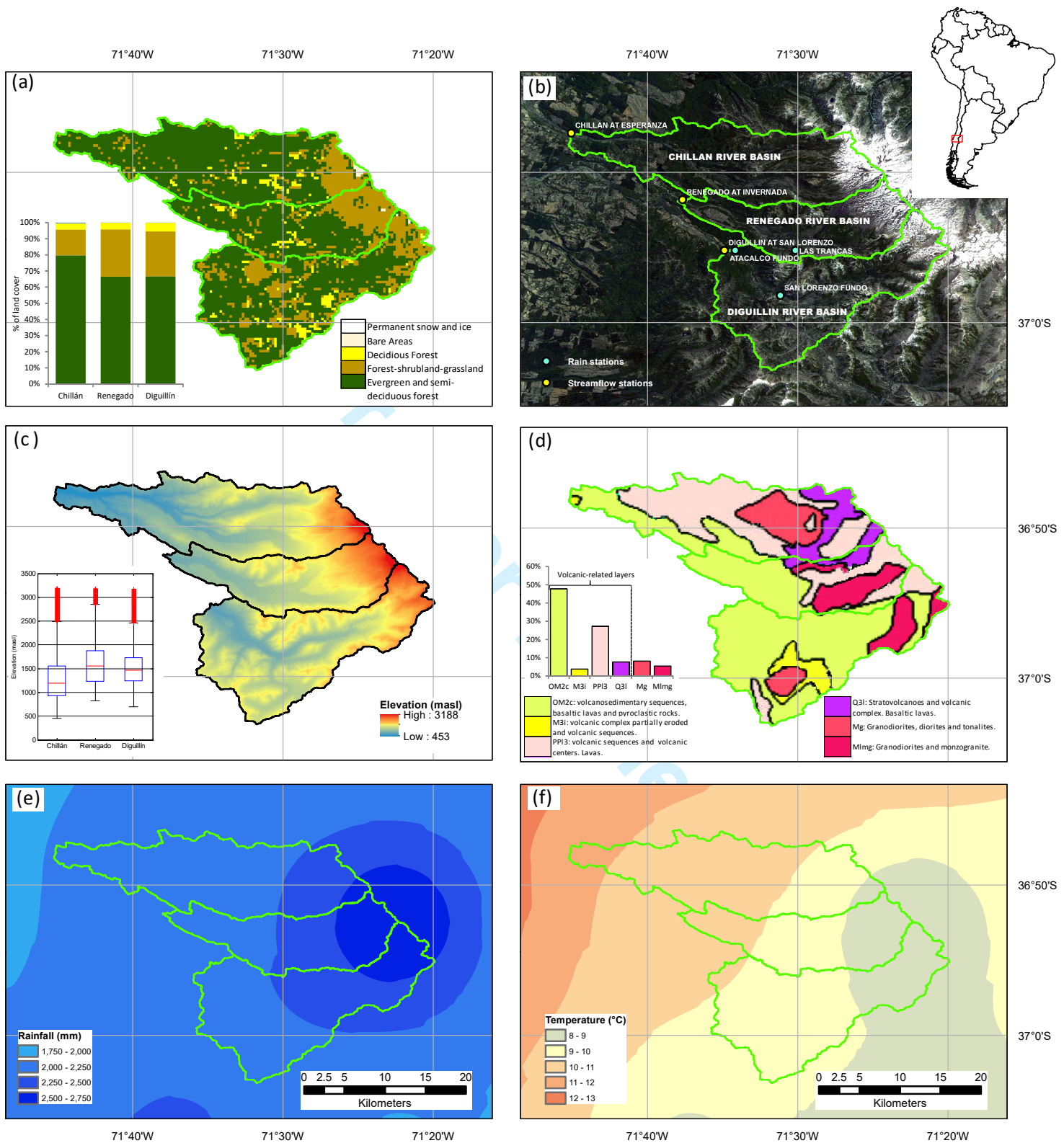


Figure 1. Study area and hydrological similarity maps, including land cover map (a), aerial view (b), terrain map (c), geologic map (d), and mean annual rainfall (e) and temperature (f) climatological maps.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60

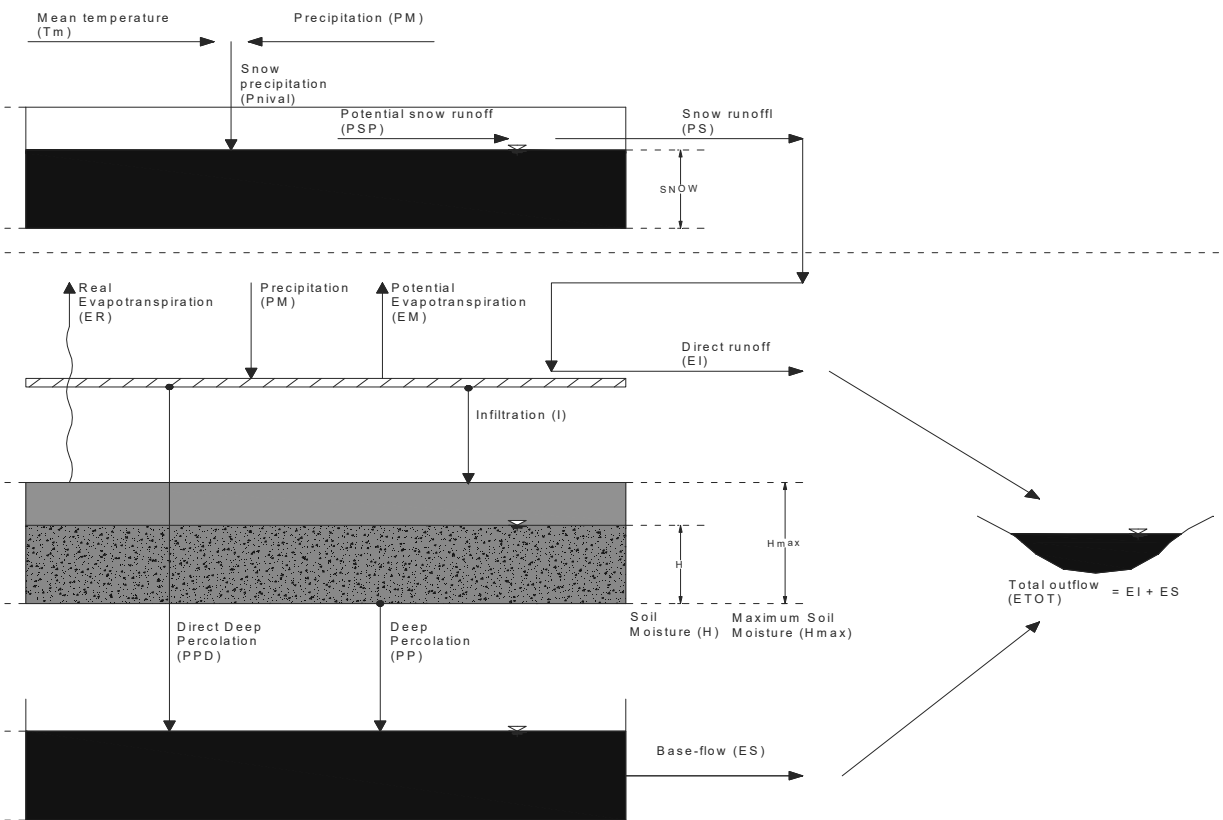


Figure 2. Diagram of the Muñoz (2010) lumped water balance model.

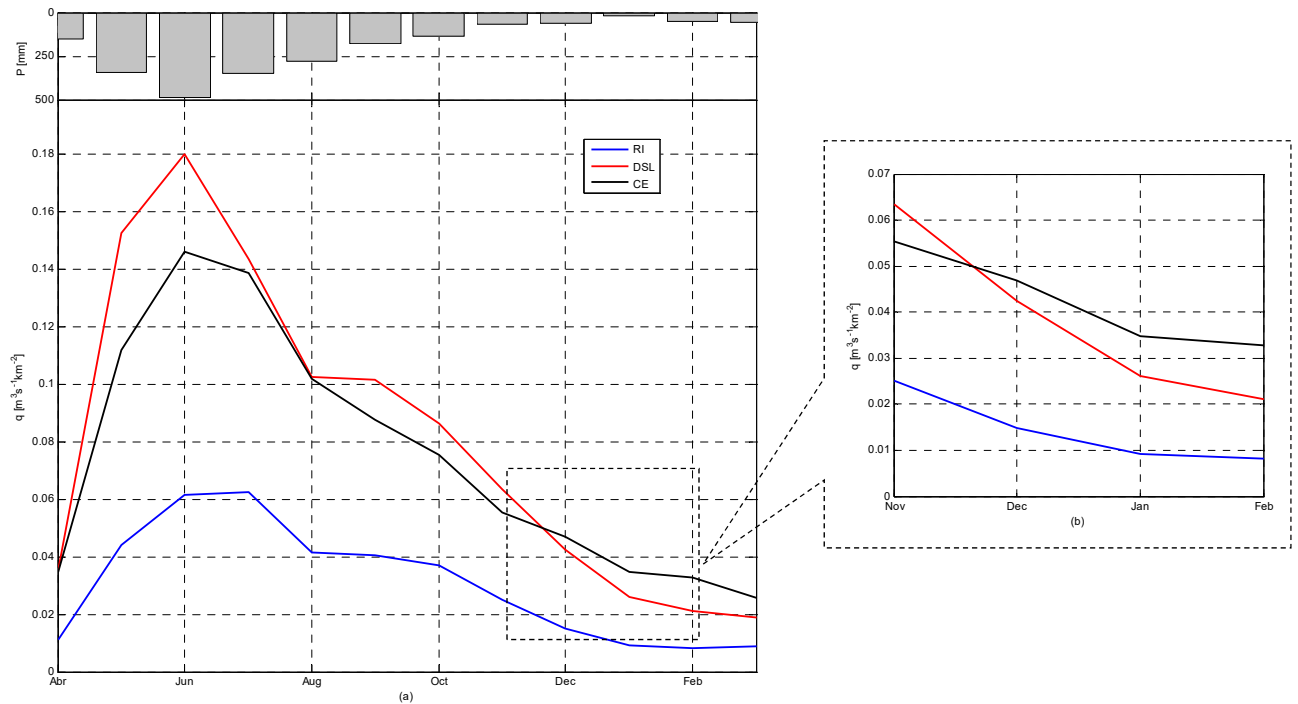


Figure 3. Seasonal precipitation and seasonal variation curves of flow per unit of area (q) for the Renegado at Invernada (RI, blue line), Diguillín at San Lorenzo (DSL, red line) and Chillán at Esperanza (CE, black line) River basins (panel a). Panel b shows a detailed view for the summer season between December and March.

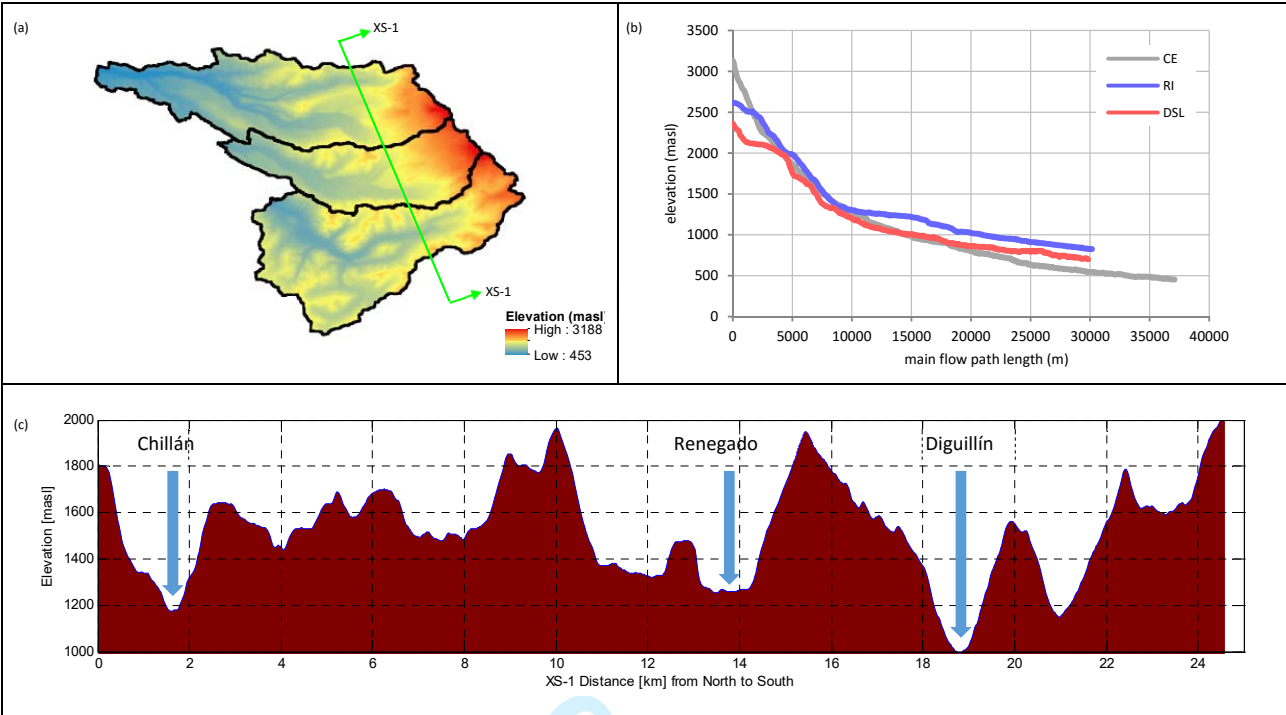
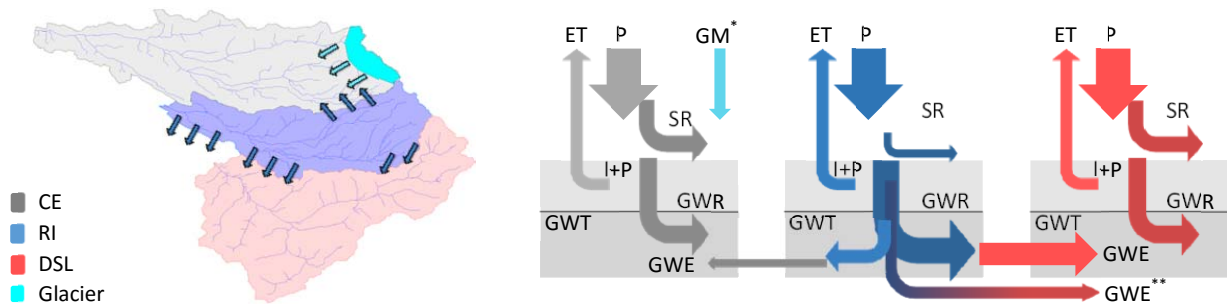


Figure 4. Cross section of the Chillán-Renegado-Diguillín hydrological system at the piedmont of the Chillán volcano.



CE: Chillán at Esperanza River basin (gray shaded area); RI: Renegado at Invernada River basin (blue shaded area); DSL: Diguillín at San Lorenzo River basin (light red shaded area).

ET: Evapotranspiration; P: Precipitation; SR: Surface Runoff; I+P: Infiltration and Percolation; GWR: Groundwater Runoff; GWT: Groundwater Table; GWE: Groundwater Exchange; GM: Glacier-melting.

* Indicates that the GM process is only occurring in summer.

** Indicates that the GWE process is also occurring downstream of the Diguillín at San Lorenzo streamflow station.

Figure 5. Conceptual interpretation of the hydrological processes and connections on the system after a review of the basins' metrics (maps), hydro-meteorological data and a water balance approach.

Table 1. Description of the model parameters, adjustment factors and range for the rainfall- and snowmelt-runoff model.

	Parameter	Description	Influence on	Range
Rainfall module parameters	C_{max}	- Maximum runoff coefficient when the sub-surface layer is saturated.	- EI	0.05 – 0.85
	P_{Lim} (mm)	- Limit of rainfall over which PPD exists.	- PPD	0- 500
	D	- Percentage of rainfall over P_{Lim} transformed into PPD.	- PPD	0 – 100
	H_{max} (mm)	- Maximum capacity of the soil layer to retain water.	- C_{max} and ER	180 - 500
	PORC	- Fraction of H_{max} that defines the soil water content restricting the evaporation processes.	- H_{crit} and ER	0 - 100
	C_k	- Subterranean runoff coefficient.	- ES	0.05 – 0.85
Snow module parameters	A	- Adjustment factor of the precipitation data.	- PM	0.80* – 2.50
	M (mm °C ⁻¹)	- Parameter of the Degree-day method that defines the fraction of the snow storage which is melted. The method also considers a base temperature ($T_b=0$ °C) at which melting starts.	- PSP, PS	1 – 12
	DM	- Minimum rate of melting when $T_m < T_b$.	- PSP, PS	0.00 – 0.50
	F	- Fraction of the real snowmelt that goes to EI.	- EI	0.00 – 1.00

EI: Direct runoff; PPD: Direct deep percolation; ER: Real Evapotranspiration; ES: Groundwater runoff; PM: Precipitation; PET: Potential evapotranspiration; PSP: Potential snowmelt; PS: Actual snowmelt.

* For the Renegado River basin the initial range of factor A was changed to 0.50 – 2.50 because it was found to be identifiable for values close to 0.60.

Table 2. Calibration values of the input modification factor (A) and parameter, and NSE-related values for the median of the 10% best behavioral models after fixing A.

		ROCE	NSE						NSE	NSE
		A	Cmax	Hmax	D	Plim	PORC	Ck	calibration	validation
Chillán	P.1	1.240	0.364	393	34.2	113.5	42.5	0.284	0.87	0.86
	P.2	1.299	0.362	388	33.9	94.5	43.1	0.280	0.87	0.87
Renegado	P.1	0.655	0.290	417	41.0	117.4	31.9	0.534	0.85	0.81
	P.2	0.599	0.360	390	24.4	128.2	33.5	0.635	0.82	0.84
Diguillín	P.1	1.298	0.417	398	21.0	97.3	54.6	0.402	0.90	0.88
	P.2	1.315	0.479	402	14.9	91.3	42.9	0.333	0.89	0.90
System	P.1	1.135	0.408	368	28.5	110.1	43.7	0.317	0.89	0.90
	P.2	1.196	0.415	388	22.5	80.8	45.6	0.287	0.91	0.91

P.1: Period between 1964 and 1979.

P.2: Period between 1980 and 1994.